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Size Reduction of an Engine Waste-Heat Driven Air-Conditioner for Passenger Cars and Light-Duty Trucks

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Abstract

An engine waste-heat driven adsorption air conditioning system is studied to provide cooling for vehicles to improve fuel economy. It is critical to reduce the size of the system in order to adopt the technology in the applications of passenger cars and light-duty trucks. Thus, a modular design using the zeolite-water working pair is modeled to determine the size of the system for the cooling requirement of 3.5kW during steady operation. The methods to reduce the module number and thus the size of the system are investigated and the control strategy to satisfy a high cooling requirement during the start-up of the cooling period is also discussed.

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1. Introduction

U.S. transportation energy use accounts for 28.1% of total U.S. energy use. Generally, the efficiency of a diesel engine is approximately 40% and the rest of the energy is rejected as waste heat to the coolant and the exhaust gas [1-4]. Furthermore, in order to meet the recently evolving standards on NO_x reduction by the Environmental Protection Agency (EPA), exhaust gas recirculation (EGR) cooling has become necessary in heavy-duty trucks. This leads to 20 to 50% increase of the heat load in the engine coolant, and thus increases the amount of energy wasted by heavy-duty vehicles [5]. Engine waste-heat driven adsorption air-conditioning system is a promising method to improve the energy efficiency.

Adsorption refrigeration is an effective way to exploit waste heat in the many applications such as ice making, air conditioning and combined cooling, heating and power systems [6,7]. Zhang

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[2] experimentally demonstrated the feasibility of using an adsorption cooling system driven by waste heat from a small diesel engine of 40 horsepower (30kW). Lambert and Jones [8] compared adsorption (solid-vapor), absorption (liquid-vapor), Stirling and Peltier coolers, and concluded that adsorption heat pump is the most practical technology for automobiles. They [9] also reported detailed design and analysis of critical components of the system. Zhong et. al [10] investigated an adsorption air-conditioning system for heavy-duty trucks with recent emission control devices. In order to exploit the waste-heat driven adsorption system to passenger cars and light-duty trucks, it is critical to reduce the size of the system. In this work, the modular design of an adsorption system is presented and its transient performance is simulated in order to determine the size of the system for 3.5kW cooling. Methods to reduce the module number and thus the size of the system are studied, and the strategies to satisfy the cooling requirement during start-up period are also discussed.

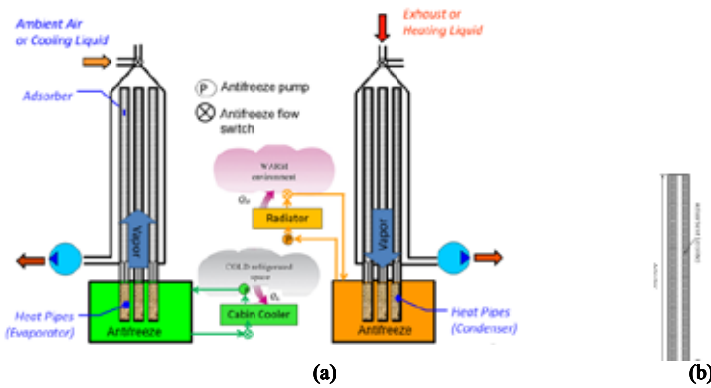


Fig. 1. (a) system schematic with two sets of modules; (b) one individual module

2. Heat-Driven Adsorption Cooling System

The adsorption cooling system shown in Fig. 1(a) includes two sets of modules and a secondary loop with a radiator, a cab core and pumps. An individual modular assembly shown in Fig. 1(b) contains an adsorber, a heat-pipe type heat exchanger and an adiabatic section in between. The complete module is a sealed vessel under vacuum when water is used as the refrigerant. When heat is removed from the adsorber, the adsorbent adsorbs water vapor, resulting in the vaporization of water in the heat exchanger. This process provides cooling and is called adsorption phase. A sequential desorption process is followed by supplying heat to the water-bonded zeolite in the adsorber. Water vapor is then released from the adsorber and flows into the heat exchanger where it is condensed and stored in a liquid phase. Two sets of modules operate alternatively in adsorption and desorption phases in order to provide continuous cooling and they switch every half of cycle period. The secondary loop with antifreeze flow is used to exchange energy between the heat exchangers of the two module sets, the vehicle cab and the ambient.

The heat used to supplied to the system during desorption phase is obtained from engine exhaust gas. The exhaust gas through a tailpipe is typically in the temperature range of 150°C to 450°C [11]. Different from traditional engines, exhaust gas is now treated for particles and NO_x using after-treatment devices and thus is cleaner and less corrosive for the adsorption system. Recovering waste heat from the exhaust gas can improve the overall engine efficiency and improve fuel economy. Ambient air flow can be used in

the adsorption phase to remove heat from the adsorber, resulting in the cooling effect to condition the cabin of a vehicle.

3. Model

The performance of an adsorption system is dominated by the mass, momentum and energy transport processes in an individual module. Assuming that the two sets of modules and the individual module in each set in Fig.1 operate independently of one another, the model focuses on the performance of a single module. The module is treated as having spatially uniform but time varying properties (transient lumped parameter analysis). The parameters used in the model and the baseline conditions are listed in Table 1. Hence, the mass conservation in an adsorber is described as following:

$$\frac{d(m_{zeo} + m_{lw} + m_{vw} + m_{metal})}{dt} - \dot{m}_{HX} = 0 \quad (1)$$

where $\dot{m}_{HX}$ is the mass flow rate of water vapor from the connected heat exchanger and is proportional to the pressure difference between the adsorber and the heat exchanger of the module,

$$\dot{m}_{HX} = f\Delta P = f(P_{HX} - P_{sorb}) \quad (2)$$

f is the friction resistance between the adsorber and the heat exchanger. $\dot{m}_{HX}$ is positive when water vapor flows from the heat exchanger into the adsorber during adsorption but negative during desorption. The mass adsorption capacity Y is defined as

$$Y = \frac{\text{adsorbed water (kg)}}{\text{dry adsorbent (kg)}} = \frac{m_{lw}}{m_{zeo}} \quad (3)$$

Because the mass of zeolite and the metal vessel remains constant over time, eq. (1) becomes

$$m_{zeo} \frac{dY}{dt} + \frac{dm_{vw}}{dt} - \dot{m}_{HX} = 0 \quad (4)$$

The adsorption rate dY/dt is simulated using the linear driving force (LDF) model with an effective rate coefficient k_{LDF} :

$$\frac{dY}{dt} = k_{LDF}(Y_{Eq} - Y) \quad (5)$$

where Y_{Eq} is a function of the adsorbent temperature and water vapor pressure in the adsorber and is evaluated using the experimental correlation by Gorbach et al. [12]. The effective rate coefficient k_{LDF} is determined by the diffusivity, the porosity of the adsorbent particle, the radius of the adsorbent pellet, crystal radius, etc. [13].

Energy Conservation of the adsorber gives

$$\frac{d(m_{zeo}u_{zeo} + m_{lw}u_{lw} + m_{vw}u_{vw} + m_{metal}u_{metal})}{dt} = \dot{Q}_{sorb} + \dot{m}_{HX}h_{HX}(T_{HX}) \quad (6)$$

where all properties are evaluated at T_{sorb} except that h_{HX} is evaluated at T_{HX} . $\dot{m}_{HX}$ is defined previously by eq. (2), and $\dot{Q}_{sorb}$, the heat transfer rate between the external fluid flow and the adsorber is given by

$$\dot{Q}_{sorb} = UA_{sorb}(T_{gas} - T_{sorb}) \text{ and } T_{gas} = \begin{cases} T_{air}, & \text{adsorption} \\ T_{exhaust}, & \text{desorption} \end{cases} \quad (7)$$

Neglect the thermal mass of the metal, treat water vapor as ideal gas, and substitute $du = CdT$ into eq.(6),

$$\begin{aligned} & (m_{\text{zeo}}C_{p,\text{zeo}} + m_{\text{zeo}}C_{p,\text{lw}}Y + m_{\text{vw}}C_{v,\text{vw}})\frac{dT_{\text{sorb}}}{dt} + m_{\text{zeo}}C_{p,\text{lw}}T_{\text{sorb}}\frac{dY}{dt} + T_{\text{sorb}}C_{v,\text{vw}}\frac{dm_{\text{vw}}}{dt} \\ & = \dot{Q}_{\text{sorb}} + \dot{m}_{\text{HX}}h_{\text{HX}}(T_{\text{HX}}) \end{aligned} \quad (8)$$

Combined with the mass transfer from eq. (4), energy conservation of the adsorber becomes

$$\begin{aligned} & (m_{\text{zeo}}C_{p,\text{zeo}} + m_{\text{zeo}}C_{p,\text{lw}}Y + m_{\text{vw}}C_{v,\text{vw}})\frac{dT_{\text{sorb}}}{dt} \\ & = \dot{Q}_{\text{sorb}} + \dot{m}_{\text{HX}}[h_{\text{HX}}(T_{\text{HX}}) - u_{\text{vw}}] + m_{\text{zeo}}\frac{dY}{dt}[\beta h_{\text{fg}} - P_{\text{sorb}}(v_{\text{vw}} - v_{\text{lw}})] \end{aligned} \quad (9)$$

where β is the ratio of the enthalpy change of adsorption to the enthalpy of vaporization (h_{fg}), and is derived based on the Clapeyron equation using the equilibrium data of water in zeolite [14]. The left side of the equation is related to the temperature change in the adsorber. The first term of the right side is heat transfer rate, the second term accounts for the energy difference of water vapor between the adsorber and the heat exchanger of a module, and the third term represents the energy change associated with adsorption or desorption process. For the heat exchanger of a module, neglect its thermal mass and the energy transport process is simplified as

$$\dot{Q}_{\text{HX}} = \dot{m}_{\text{HX}}h_{\text{fg}} \quad (10)$$

$$\dot{Q}_{\text{HX}} = UA_{\text{HX}}(T_{\text{HX}} - T_{\text{fluid}}) \quad (11)$$

where UA_{HX} is the thermal conductance of the heat exchanger and T_{fluid} is equal to $T_{\text{fluid, evp}}$ in adsorption phase and $T_{\text{fluid, con}}$ in desorption process.

Table 1. Parameters of the model and the baseline conditions

Parameter	Symbol	Value
Heat conductance of the adsorber	UA_{sorb}	19.4 W/°C
Heat conductance of the heat-pipe type HX	UA_{HX}	200.0 W/°C
Specific heat of the adsorbent (zeolite)	$C_{p,\text{zeo}}$	920 J/kg-°C
Specific heat of the refrigerant (water)	$C_{p,\text{lw}}$	4210 J/kg-°C
Mass of the adsorbent (zeolite) in one module	m_{zeo}	1.0 kg
Vapor volume in one module	V_{vw}	0.1 m ³
Friction resistance between the adsorber and the HX	f	0.003 kg/ kPa-s
Start-up cooling power	$\dot{Q}_{\text{start}}$	7.5kW
Steady-state cooling power	$\dot{Q}_{\text{steady}}$	3.5kW
Temperature preferred in the cab (COLD space around cab core)	T_{cab}	23 °C
Exhaust gas temperature for desorption	T_{exhasut}	250 °C
Ambient air temperature (WARM environment around radiator)	T_{air}	38 °C
Temperature of antifreeze flow (evaporator or condenser)	$T_{\text{antifreeze, evp}}$ $T_{\text{antifreeze, con}}$	7 °C 38 °C
Overall effective rate coefficient of zeolite in LDF model*	k_{LDF}	0.0022 s ⁻¹
Cycle period	Δt	30 minutes

The total heat required per cycle to drive the one module is

$$Q_{\text{desorption}} = 2 \int_0^{\frac{\Delta t}{2}(\text{desorption})} \dot{Q}_{\text{sorb}} dt \quad (12)$$

And correspondingly the cooling provided to the vehicle per operating cycle is

$$Q_{\text{cooling}} = 2 \int_0^{\frac{\Delta t}{2}(\text{adsorption})} \dot{Q}_{\text{HX}} dt \quad (13)$$

As the cooling capacity required by the vehicle cabin increases, multiple modules should be installed in each set of the system. Assuming that each module operates independently, the COP of an adsorption system is calculated as

$$\text{COP} = \frac{Q_{\text{cooling}}}{Q_{\text{desorption}}} \quad (14)$$

Neglect the heat loss in the secondary loop, the number of the modules in each unit to meet the vehicle air-conditioning need is estimated by

$$N = \frac{\dot{Q}_{\text{steady}} \Delta t}{Q_{\text{cooling}}} \quad (15)$$

4. Results and Discussion

4.1. Effect of cycle operating period on module number

The module number required in each set of the system is listed in Table 2 for various cycle periods, and the cycle period of 30 minutes requires the minimum number of modules. As shown in Fig.1, two sets of modules in a system switch functions between the adsorption and desorption phases every half cycle period. That is, in order to provide cooling of 3.5kW with a minimum number of modules, each set of the adsorption system should contain 12 modules and switch functions every 15 minutes. The optimal module number is determined by the rate of cooling produced per cycle listed as Q_{cooling} in Table 2. For a given operation period, take 120 minutes as an example, a system operated with the cycle period of 30 minutes, 60 minutes and 120 minutes completes 4 cycles, 2 cycles and 1 cycle, respectively. The total cooling rate over a 120-minute operation is listed in Table 3 for a system operated with these three cycle periods. As shown in Table 3, 30-minute cycle provides large cooling rate than the others. As a result, the module number for 30-minute cycle is fewer than the others. The cooling provided by a system of various cycle periods is a characteristic of the transient heat and mass transfer: the longer a module is in adsorption phase, the less the cooling rate and mass adsorption capacity of the adsorbent are. The cooling capacity reaches its maximum when the driven potential for mass transfer reaches the maximum and then decreases rapidly [10].

Table 2 Module number for various cycle periods

Cycle Period, Δt (minute)	Q_{cooling} (kJ)	$Q_{\text{desorption}}$ (kJ)	COP	No. of Module (steady, 3.5kW)	$\dot{Q}_{\text{evap, max}}$ (W)	$\dot{Q}_{\text{max, set}}$ (kW)
20	289	1261	0.230	14	349	5.1
30	508	1166	0.436	12	457	5.7
40	614	1371	0.448	13	493	6.7
60	740	1520	0.487	17	522	8.9
100	803	1630	0.492	26	536	14.0
120	808	1623	0.498	31	535	16.7

Table 3 Heat Transfer Rate over a Given Period

Cycle Period, Δt (minute)	No. of Module (steady, 3.5kW)	$Q_{\text{cooling, Per cycle}}$ (kJ)	$Q_{\text{cooling, 120min}}$ (kJ)
30	12	508	2032
60	17	740	1480
120	31	808	808

4.2. Effect of heat and mass transfer on module number

The effect of heat and mass transfer on the module number is illustrated in Tables 4-6 and these results are for the system under the conditions of Table 1 except UA_{sorb} and k_{LDF} . The heat transfer of a module, represented by UA_{sorb} , can be improved by adding fins or metal foams in the adsorber of the module. The

effective rate coefficient k_{LDF} is an overall effective mass transfer coefficient and varies widely depending on the system and conditions. Diffusion resistances to mass transfer of adsorbents have two distinct types: the micro-pore resistance of the crystals and the macro-pore resistance of the pellet. This is because many commercial adsorbents consist of small microporous crystals (typically 1 to 10 μm) formed into a macroporous pellet of suitable dimensions, porosity and mechanical strength. Small crystal size can minimize intra-crystalline resistance but may also reduce the macro-pore diffusivity. The macro-pore resistance can be decreased by reducing the pellet size. For example, k_{LDF} depends on the square of the particle radius and can be increased by reducing the size of the pellets.

Though the improvement of either heat transfer or mass transfer reduces the module number, the effect of increasing mass transfer is more pronounced. As shown in Table 4, doubling UA_{sorb} reduces the module number from 12 to 11; and doubling k_{LDF} results in the module number to 9 as shown in Table 5. If both heat transfer and mass transfer parameters are doubled, the module number can be reduced from 12 to 8 as shown in Table 6. Therefore, advanced designs such as metal fins, consolidated zeolite as discussed in [6] should be applied to the modules so that the size of the system can be appropriate for the applications of passenger cars and light-duty trucks where space for the air-conditioning system is highly restricted.

Table 4 Module number for the design with increased heat transfer

Adsorber design	UA_{sorb} (W°C)	$Q_{cooling}$ (kJ)	No. of Module (steady, 3.5kW)	$\dot{Q}_{evap,max}$ (W)	$\dot{Q}_{max,set}$ (kW)
Basic	19.4	508	12	457	5.7
Advanced	38.8	543	11	551	6.4

Table 5 Module number for the design with increased mass transfer

Adsorber design	k_{LDF} (s^{-1})	$Q_{cooling}$ (kJ)	No. of Module (steady, 3.5kW)	$\dot{Q}_{evap,max}$ (W)	$\dot{Q}_{max,set}$ (kW)
Basic	0.0022	508	12	457	5.7
Advanced	0.0044	670	9	705	6.7

4.3. system operation during the start-up of cooling period

The start-up of a cooling period usually requires much higher cooling capacity than the steady operation for a vehicle and hence special care should be taken in the system operation at the beginning. The transient performance of the system may be helpful to satisfy the large cooling requirement. As shown in Fig. 2(a), the maximum cooling power is reached within a few minutes after an adsorption phase starts. The values of the maximum cooling power under the various conditions are listed as $\dot{Q}_{evap,max}$ in Tables 2 and 4-6. $\dot{Q}_{max,set}$ in the tables are the product of $\dot{Q}_{evap,max}$ and the module number in one set of a system, indicating the maximum cooling power that one module set of the system can provide at the beginning of a cooling process. As listed in the tables, the maximum cooling power is much larger than that of 3.5kW required for steady operation. The transient performance of the module is advantageous for the start-up period.

Table 6 Module number for the design with increased heat and mass transfer ($UA_{sorb}=38.8\text{W}^{\circ}\text{C}$ and $k_{LDF}=0.0044\text{s}^{-1}$)

Adsorber design	$Q_{cooling}$ (kJ)	No. of Module (steady, 3.5kW)	$\dot{Q}_{evap,max}$ (W)	$\dot{Q}_{max,set}$ (kW)
Basic	508	12	457	5.7
Advanced	739	8	951	9.1

Moreover, two sets of modules in the system could be operated in the adsorption phase and provide cooling at the start-up of a cooling period. Usually the start-up of a cooling period occurs when a vehicle starts running after a period of parking. Heat from a heating device such as fuel fire heater could be supplied to both module sets of the adsorption system during parking period. Thus, both module sets are ready for the adsorption phase when the cooling is required for the vehicle. It should be noted that one set of modules must stop providing cooling and switch to desorption phase once the start-up period, usually less than 5 minutes, is over.

5. Conclusion

An engine waste-heat driven adsorption air-conditioner system is studied to improve the fuel economy of passenger cars and light-duty trucks. The system has two sets of modules operating alternatively in the adsorption phase and desorption phase. The module set is cooled by ambient air and provide cooling during adsorption phase. During desorption phase, the module set is heated by engine waste heat and prepared for the adsorption phase. It is critical to reduce the size of the system for the space restriction in the application of passenger cars and light-duty trucks. This study reported the effects of cycle operating periods and the coefficient of heat and mass transfer on the module numbers. The results show that the effect of mass transfer on module number is more pronounced than heat transfer. A system operated in 30-minute per cycle requires fewer module number than 20-minute, 60-minute, and 120-minute cycle. This behavior is caused by the transient performance of the module. The transient performance is advantageous for the start-up of a cooling period when the cooling requirement is much higher than that in steady operation.

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